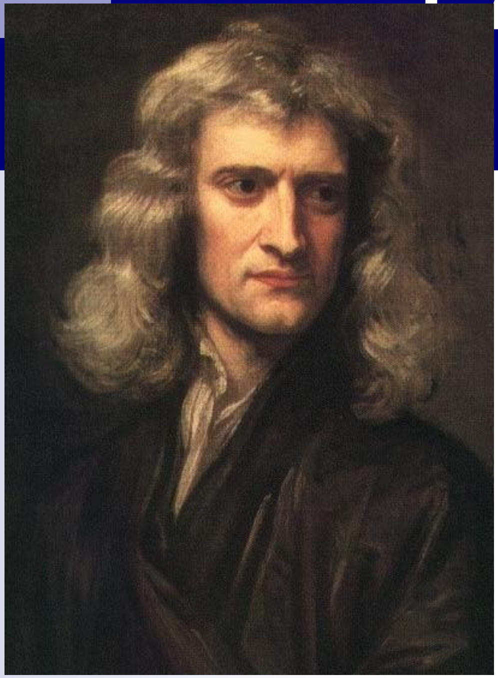
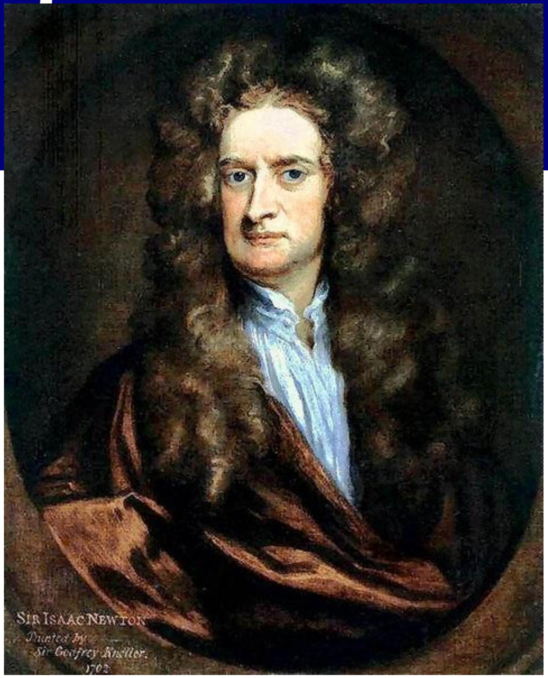
Issac Newton (1643-1727)





- If anyone can be called “the founder of modern science”, then it should be Newton.

- At the age of 25, during 18 months when Cambridge University was closed because of an epidemic of plague, Newton
  - developed mathematical calculus;
  - founded optics, the science of light propagation;
  - initiated his work on (what is now called Newtonian) mechanics.

- He was made the Lucasian Professor of Mathematics at Trinity College at the age of 26.

Three years after that he was elected to the Royal Society of London, and he spent the rest of his scientific career participating in various committees and meetings.

- His main work is called *Philosophiae Naturalis Principia Matematica* (*The Mathematical Principles of Natural Philosophy*), or, in short, *Principia*. It was published in 1687.

Newton as a Person

- He was very closed and unapproachable, constantly in fear of competition or of being proven wrong. Never-the-less, his friends remained loyal to him all life long.
- He rigged a formal resolution of his argument with Leibnitz about who first invented calculus.
- He published a draft of Flamsteed's book without permission.
- At the age of 50 he suffered a mental breakdown and spent the rest of his life as a head of British Mint – a mere sinecure.

Newton’s Laws of Motion

- He described his three laws of motion in *Principia*.
- Newton’s laws form the foundation of all physics.
- Einstein’s Theory of Relativity extends Newton’s laws to the limit of very high speeds and very strong gravity, but it does not overrule them.
- Quantum Mechanics extends Newton’s laws to the world of elementary particles, but it remains consistent with them.

First Law

- *An object at rest or in a state of uniform motion will remain at rest or in uniform motion, unless acted upon by a net external force*

- This is also known as the ***law of inertia***. Inertial motion is a motion with the constant ***velocity***. Thus, a force always produces a change in velocity, or, in other words, an ***acceleration***.

Second Law

- *The acceleration of an object is proportional to the net force applied to it.*

- The coefficient of proportionality is called ***the inertial mass***. Mathematically, the second law is expressed like this:

$$\vec{F} = m\vec{a}.$$

Linear Momentum

- A ***linear momentum*** is a very important characteristic of an object in mechanics. It is a product of the object's mass and its velocity:

$$\vec{p} = m\vec{v}.$$

- You can think of it as of a ***measure of inertia***.

Linear Momentum II

- Change in velocity is acceleration:

$$\vec{a} = \frac{d}{dt}\vec{v}$$

- Change in momentum is then the force:

$$\vec{F} = \frac{d}{dt}\vec{p}$$

Conservation of Momentum

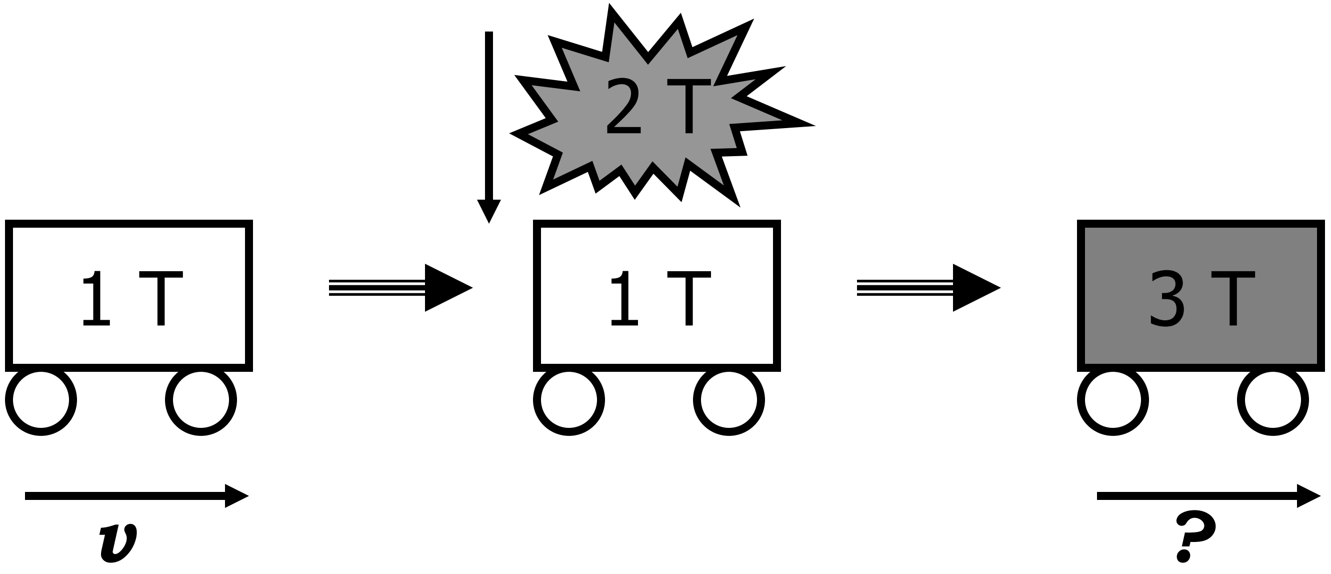
- **Important case**: in the absence of the net external force the linear momentum of an object is conserved.

- This is called the ***law of conservation of momentum***. It is more general than the law of inertia, because it is a combination of the first and the second Newton's laws .

$$\vec{p} = m\vec{v} = \mathrm{const}$$

Question:

- An empty, freely rolling boxcar is suddenly loaded from the top with a load of coal twice the mass of an empty boxcar. How will the speed of the boxcar change?



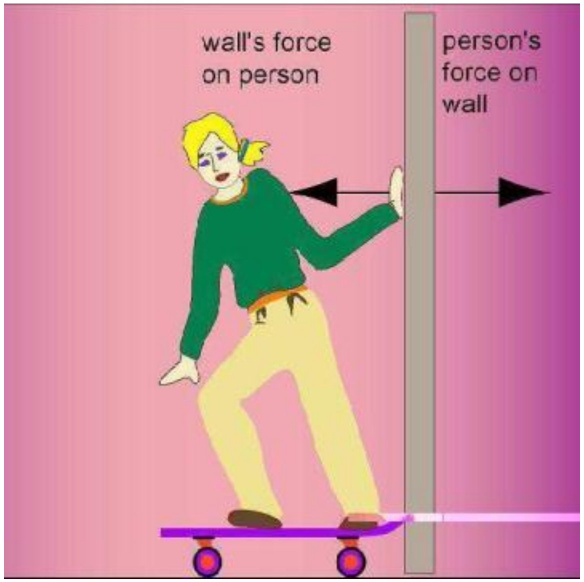
- **A:** It will not change.
- **B:** It will be half of the original speed.
- **C:** It will be third of the original speed.
- **D:** It will be twice the original speed.

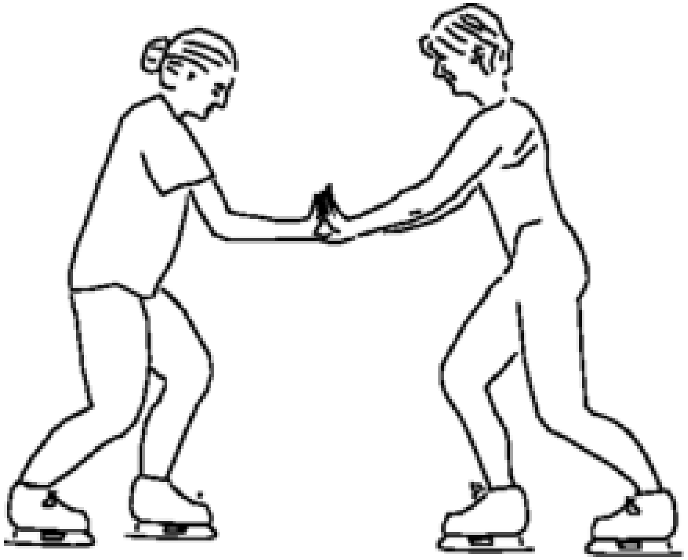
Newton’s Third Law

- For every action, there is an equal and opposite reaction.

- Example: If object A exerts a force on object B, then object B exerts an equal and opposite force on object A.

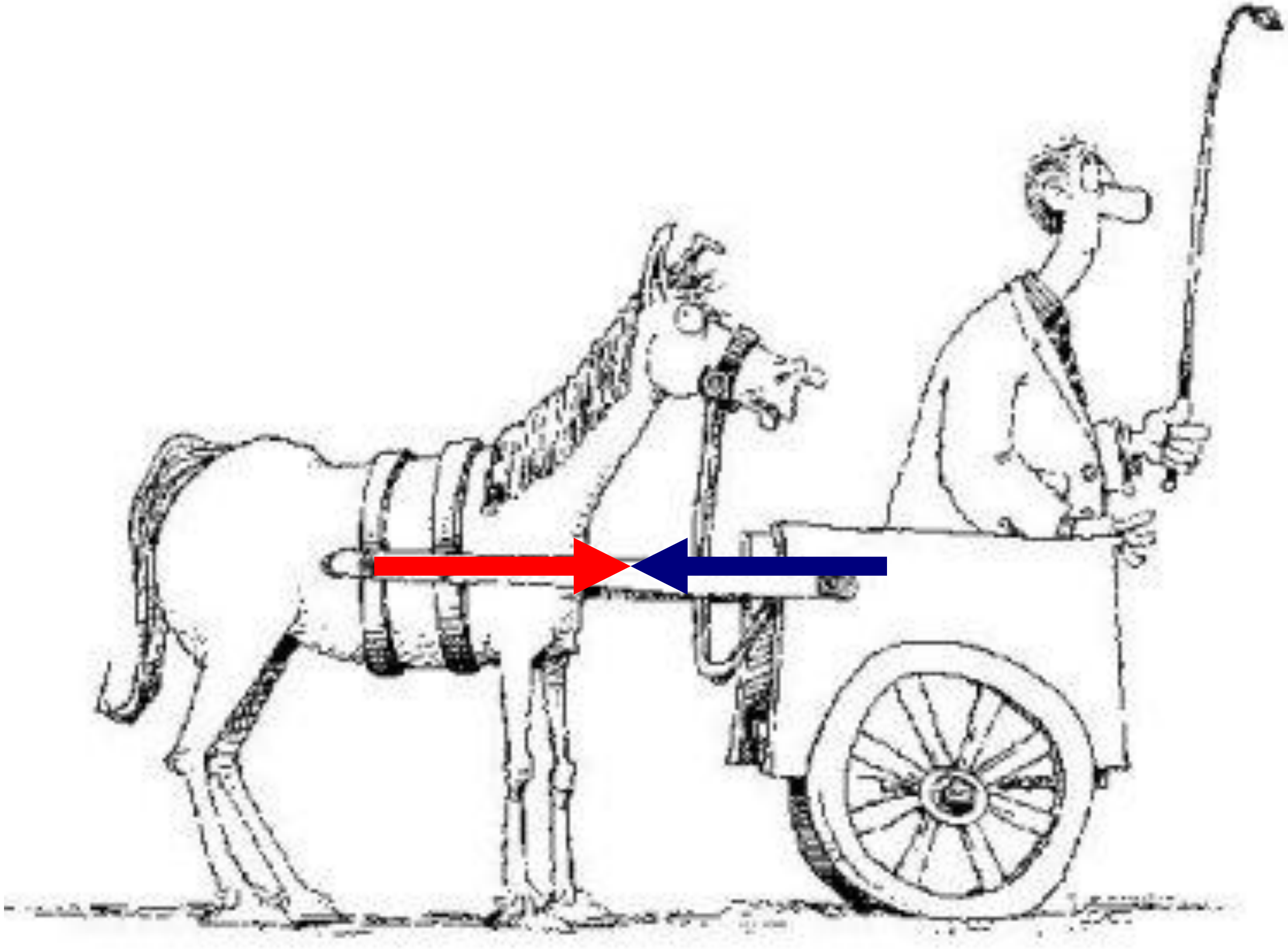
Newton’s Third Law



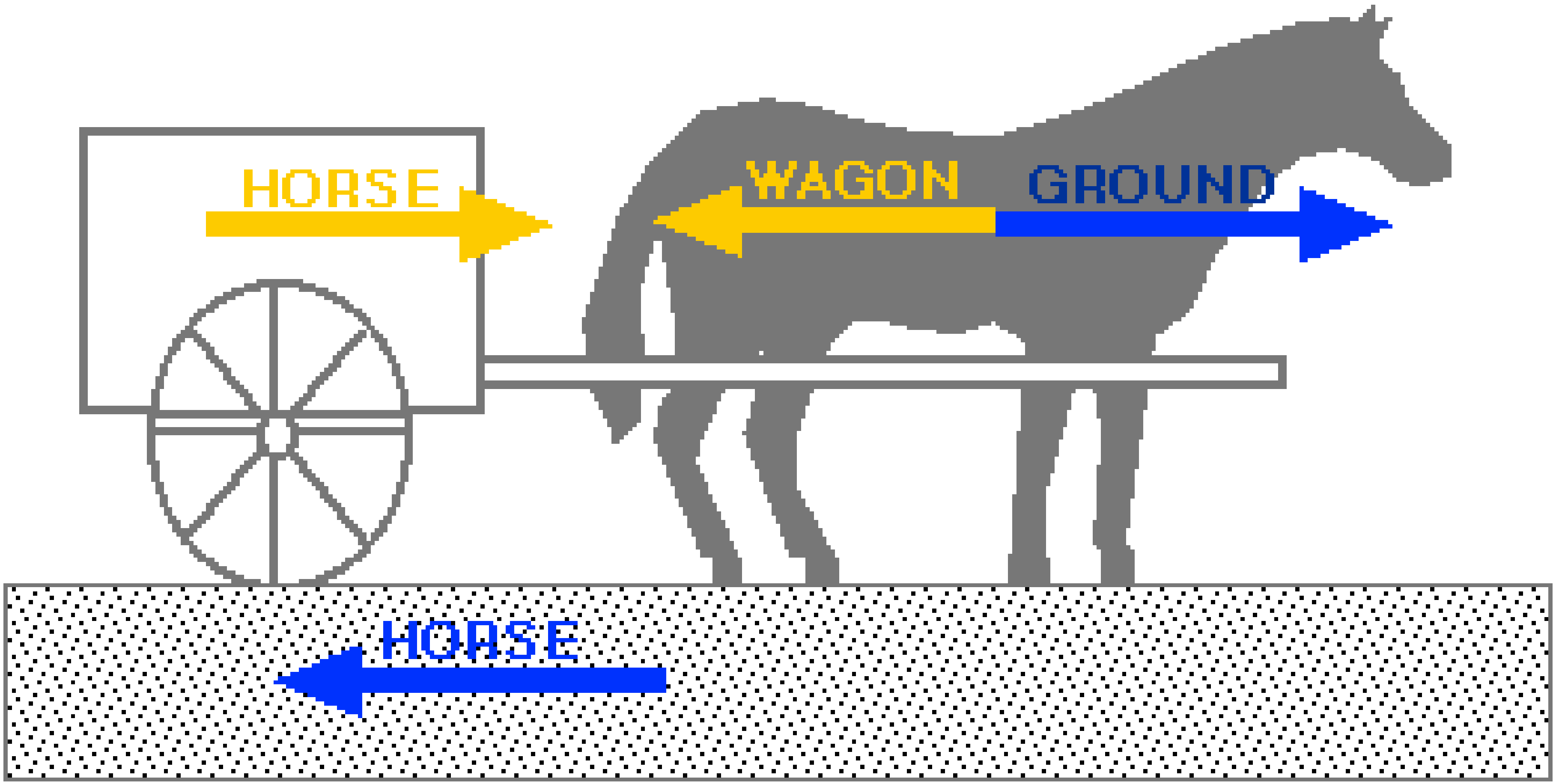


Guess the outcome…

Newton’s Third Law



Newton's Third Law



The Law of Gravity

- At the time of Newton it was perfectly understood that there existed a force called "gravity" that made all objects fall to the ground.
- Newton conjectured that the same force was responsible for the Moon orbiting the Earth and the planets orbiting the Sun.

- If that was indeed the case, the acceleration acting on the Moon should be about 3600 weaker than the acceleration of objects to fall to the ground.

- Since the distance to the Moon was about 60 times the size of the Earth, the force of gravity had to obey the *inverse square law*:

$$\frac{1}{3600} = \frac{1}{60^2}$$

- Using the inverse square law for the gravitational force, Newton was able to derive all three Kepler's law of planetary motions.

- Using additional arguments, Newton finally arrived at the formula that gives the force of gravity between two objects with masses M_1 and M_2:

$$F_g = G\frac{M_1 M_2}{R^2}$$

where R is the distance between two objects, and G is a ***fundamental constant***, i.e. a number that is the same at all times and everywhere in the universe.

If one of the objects is much larger than the other (as, for example, the case of the Sun and a planet), then the mass of the larger object is usually denoted by *M*, and the mass of the smaller object is denoted by *m*:

$$F_g = G\frac{mM}{R^2}$$

Measuring *G*

- Newton's gravitational constant ***G*** is by far the ***worst*** known fundamental constant:

$$G = (6.6726 \pm 0.0003) \times 10^{-11}\,\frac{\mathrm{m}^3}{\mathrm{kg\,s}^2}$$

- The reason for that is that gravity can be measured very precisely, but it always comes as ***GM***, but it is *very* hard to measure masses of various objects accurately. We do know $GM_\odot$ for the Sun better:

$$GM_\odot = 1.32712440018(8) \times 10^{20}\,\frac{\mathrm{m}^3}{\mathrm{s}^2}$$

- Now we can understand why all the objects fall to the ground with the same acceleration (and, thus, in the same time, if they fall from the same height).
- From Newton's Second Law:

$$mg = F_g = G\frac{mM}{R^2}$$

- *m* can be cancelled on both side, so it disappears.

$$g = G\frac{M}{R^2}$$

$$g = G\frac{M}{R^2}$$

There is no *m* any more in this equation, which means that *g* is independent on the mass of a falling object. At the surface of the Earth

$$g = 9.8\,\mathrm{m/s^2}$$

Oops! Do we have a problem?

- In the equation:

$$g = G\frac{M}{R^2}$$

G is constant (does not change no matter what), *M* is the mass of the Earth (does not change no matter what), but *R* is the distance to the center of the Earth, and it can change.

- On Skydeck (Sears tower) we are 412 meters further from the center of the Earth, and we therefore should weight less on Skydeck than on the ground.

Question: True or false?

Gravitational vs Inertial Mass

Recall: all objects fall to the ground with the same acceleration, because the gravity force is proportional to the mass:

$$\cancel{m}g = G\frac{\cancel{m}M}{R^2} \quad \Rightarrow \quad g = G\frac{M}{R^2}$$

But who said that two little m(s) are the same?

- ***Inertial mass*** is a measure of inertia, it enters the Second Law of Newton:

$$F = m_{\mathrm{in}} a$$

- ***Gravitational mass*** is a measure of how a body reacts to the force of gravity:

$$F = G m_{\mathrm{gr}} \frac{M}{R^2}$$

There is no a priori reason why these two should be the same!

(Weak) Equivalence Principle

- Equality of inertial and gravitational masses is called a ***(weak) equivalence principle***: inertial and gravitational masses are ***equivalent.***

$$m_{\mathrm{in}} = m_{\mathrm{gr}}$$

- Equivalence principle has been verified experimentally.

Tests of Equivalence Principle

1590, Galileo Galilei:	1 part in 50
1686, Isaac Newton:	1 part in 1,000
1832, Friedrich Bessel:	1 part in 50,000
1908, Baron von Eotvos:	1 part in 100 million
1930, J. Renner:	1 part in 1 billion
1964, Dicke et al:	1 part in 100 billion
1972, Braginsky, Panov:	1 part in 1 trillion
2008, Adelberger et al:	1 part in 30 trillion
2013, Galileo:	1 part in 100 quadrillion

Energy

- Thomas Young (1773 – 1829) first coined the term “energy”. He also disproved Newton’s corpuscular theory of light.
- At the time of Newton, the concept of “energy” existed. Leibnitz called it “vis viva”.
- Both, Leibnitz and Newton understood the process of energy conversion – for example, the kinetic energy of motion gets transformed into heat by friction.

Many Faces of Energy

- Energy comes in many faces:
  - ***Kinetic***
  - ***Thermal***
  - ***Gravitational***
  - ***Electromagnetic***
  - ***Rest energy***
  - ***Nuclear***
  - ***Atomic***
  - ***Chemical***

Conservation of Energy

- The conservation of energy implies that the sum of **all** kinds of energy of a closed (i.e. not interacting with something else) system is always conserved (as long as the system exists).
- Any particular kind of energy does not have to be conserved.

There are no exceptions to this law!!!
Never ever!!!
Nowhere!!!

- *There is a fact, or if you wish, a law, governing natural phenomena that are known to date. There is no known exception to this law; it is exact, so far we know. The law is called* ***conservation of energy****; it states that there is a certain quantity, which we call energy, that does not change in manifold changes which nature undergoes. That is a most abstract idea, because it is a mathematical principle; it says that there is a numerical quantity, which does not change when something happens. It is not a description of a mechanism, or anything concrete; it is just a strange fact that we can calculate some number, and when we finish watching nature go through her tricks and calculate the number again, it is the same.*

——The Feynman Lectures on Physics

Binding Energy

- Energy has a *sign* – it can be positive or negative. Negative energy is also called **binding energy**.
- If an object has binding energy, some other energy needs to be expended to disperse or destroy that object.
- Gravitational energy is always negative (= binding); nuclear/atomic, or chemical energy can be positive or negative.

Gravitational Energy

- Gravitational energy is always binding – gravity always pulls things together.

$$-G\frac{M^2}{R}$$

- If an objects gets more massive or smaller, then it binding energy gets more negative (often it is said – mathematically incorrectly – that its "*binding energy increases*").
- That results in **production** of some other energy.

Escape Velocity

- Conversely, to take a part of a gravitating object away requires an **expenditure** of energy.
- To send a spaceship off the Earth (an asteroid off the solar system, a star off a galaxy, …), the expended energy should be converted into the kinetic energy of motion.
- The speed that corresponds to that energy is called the **escape velocity**.

$$v_{\mathrm{esc}} = \sqrt{\frac{2GM}{R}}$$